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AN EVALUATION OF DRY FILM LUBRICANTS AND SUBSTRATE MATERIALS FOR USE ON SSME GIMBAL BEARINGS

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16. Abstract

Failure of the spherical bearing shaft of the Space Shuttle Main Engine (SSME) gimbal bearing assembly was encountered during Design Verification Specification testing of the full scale engine at Rocketdyne. Investigation revealed that the failure was caused by a deficiency in the lubrication system. The dry film lubricant had broken down and the metals were severely galled. Based upon the materials and gimbal operating conditions, it was agreed by MSFC and Rocketdyne lubrication cognizant personnel that a lubricant of MoS_2 and graphite with a ceramic binder would be the best lubricant candidate for this particular application; however, the decision to implement the change could not be made without verification testing. Since full scale testing would involve very expensive hardware and elaborate test facilities, it was concluded that scaled down simulation testing should be accomplished. The Lubrication and Surface Physics Branch was requested to establish a test program, verify the proposed lubricant, and comparatively evaluate other possible lubricants and substrate material combinations. Rocketdyne also planned a concurrent test program to supplement the MSFC tests.

Four different substrate materials and eight different dry film lubricants were subjected to tests under simulated SSME environmental and stress load conditions. The test specimens were evaluated for friction and operating life. Each test specimen was subjected to cyclic operation under load until failure. The force required to move the bearing surfaces relative to each other was monitored throughout the test, thus providing analytical data for derivation of the coefficient of friction.

The MoS_2/ graphite lubricant with ceramic binder proved to be superior from the standpoint of endurance and also from the standpoint of friction reducing capabilities when applied to the titanium substrate material used on SSME. Endurance of this lubricant was approximately 16 times that of the lubricant which was being used when the SSME gimbal failed, and the overall coefficient of friction for this lubricant was less than one-third that of the lubricant which failed. It was concluded that the MoS_2/ graphite lubricant is superior for use on the SSME gimbal bearing assembly.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

TECHNICAL MEMORANDUM X-64989

AN EVALUATION OF DRY FILM LUBRICANTS AND SUBSTRATE MATERIALS FOR USE ON SSME GIMBAL BEARINGS

SUMMARY

Seven dry film lubricants were tested and compared to the dry film lubricant which was being used on the Space Shuttle Main Engine (SSME) gimbal when failure was encountered during Design Verification Specification (DVS) testing of the full scale engine at Rocketdyne. Four different substrate material combinations were also evaluated with respect to their effect on friction and endurance. The various combinations of lubricants and substrate materials tested as a part of this program are tabulated in Table 1. A total of 34 test specimens were tested. The specimens were serialized with a coded number to identify the substrate material and also the dry film lubricant type.

Based on data gathered during this program, it was concluded that the MoS_2/graphite lubricant with the ceramic binder [lubricant (B)] applied to titanium is the superior combination of substrate material and dry film lubricant for the particular application of the SSME gimbal bearings.

I. INTRODUCTION

During SSME full scale gimbal DVS testing at Rocketdyne, the main engine gimbal bearing failed (galled) after having been subjected to only 200 cycles operational and 1400 cycles nonoperational mode. The material of the bearing is titanium (Ti-6Al-6V-2Sn) and the lubricant being used at the time of failure was lubricant (A) which is identified in Table 2 and was applied in accordance with Rocketdyne Specification RAO-112-006.

When the assembly was inspected it was found that the spherical bearing shaft P/N RS008826 had galled to the extent that the surface was marked completely through the dry film lubricant.

TABLE 1. SERIALIZATION CODES FOR SUBSTRATE MATERIALS AND LUBRICANTS

Lubricant → / Code Letter ↓ Substrate Material ↓ Code	Description	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
1	Titanium Ti-6Al-6V-2Sn Heat Treated to 1.2×10^9 N/m^2 Tensile Strength	S/N 1A-1 S/N 1A-2 Two Samples	S/N 1B-1 S/N 1B-2 Two Samples	S/N 1C-2 S/N 1C-3 Two Samples	S/N 1D-2 S/N 1D-3 Two Samples	S/N 1E-3 S/N 1E-4 Two Samples	S/N 1E-2 One Sample	S/N 1E-1 One Sample	---
2	Chrome Plated Titanium Ti-6Al-6V-2Sn Heat Treated to 1.2×10^9 N/m^2	S/N 2A-1 S/N 2A-2 Two Samples	S/N 2B-1 S/N 2B-2 S/N 2B-3 Three Samples	S/N 2C-1 S/N 2C-2 Two Samples	S/N 2D-1 S/N 2D-3 Two Samples	---	---	---	---
3	Titanium Ti-6Al-6V-2Sn Clevis With Hardened 440-C Steel Pin	S/N 3A-1 S/N 3A-2 Two Samples	S/N 3B-1 S/N 3B-2 Two Samples	S/N 3C-1 S/N 3C-2 Two Samples	S/N 3D-1 S/N 3D-2 S/N 3D-3 Three Samples	---	---	---	---
4	440-C Hardened Steel	---	---	---	---	---	---	S/N 4G-1 S/N 4H-1 Two Samples	S/N 4F-1 S/N 4J-1 Two Samples

Note: First numeral of the serial number is substrate material code, see column 1.
The letter in the serial number is the code for the lubricant, see column across the top.
The last numeral of the serial number is the sample number of that particular combination of substrate material and lubricant.

TABLE 2. MANUFACTURER ADVERTISED DATA

Lubricant Code Letter	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)
Applicable Government Specifications	Mil-L- 46010		50M60434					MIL-L- 8937 MIL-L- 46010 PD-42
Primary Constituents	MoS_2 Metallic Oxide Corrosion Inhibitor	MoS_2 Graphite	MoS_2 Sb_2O_3	MoS_2 Sb_2O_3	MoS_2 Graphite	MoS_2 Graphite Different Percentages of Consti-tuents from (E)	MoS_2 Sb_2O_3 Ag	MoS_2 Sb_2O_3
Binding Agent	Resin	Ceramic	Polymide	Poly-phenylene	Inorganic Acid	Inorganic Acid	Phenolic Epoxy	Phenolic Epoxy
Cure Cycle	1.0 h @ 204°C	1.0 min @ 524°C	30 min @ Air Dry 1.0 h @ 149°C 1.0 h @ 302°C	1.0 h @ 94°C 0.5 h @ 371°C	1.0 h @ 204°C			1.0 h @ 177°C 2.0 h @ 149°C 2.5 h @ 121°C
Usable Temperature Range	-204°C +260°C	-134°C +399°C	- - +260°C	- - +427°C	-251°C +649°C	- - + -	- - + -	-204°C +343°C

It was recommended by the Lubrication Branch of the Engineering Physics Division that consideration be given to changing the lubricant to lubricant (B) (identified in Table 2). It was also recommended that a test program be established to verify that the lubricant will work for this particular application and to determine if it is the best dry film lubricant available for this application.

The gimbal bearings for previous engines were essentially the same as this one in basic design except that the SSME gimbal bearing assembly was made of titanium whereas the earlier ones were made of steel. Titanium was used to reduce the weight. It had not been demonstrated that the titanium material would withstand the loads imposed by the SSME gimbal, thus, the possibility of using some other material or combination of materials was to be considered. The different material combinations and different lubricants considered are discussed later in this report.

Several reports that MoS_2 when added to oils and greases has promoted corrosion on ferrous metals have caused concern about the use of MoS_2 based solid lubricant systems.

Excerpts of pertinent literature are given as follows:

a. Meade and Murphy SAE Preprint 656G pp(1963)

<u>Dry Lubricants and Corrosion</u>

"Resin Bonded Dry Lubricants Act as Corrosion Barrier"

b. E. E. Weismantel Lubricant Engineering 11, No. 2 97-10

1963 <u>Friction and Fretting with Solid Lubricants</u>

"Both MoS_2 and Graphite with and without Binders were Effective for Reducing Corrosion and Friction"

c. McDonnell Douglas Contract AF3365711215

<u>Effects of MoS_2 on Stainless Steel at 800°F</u>

"There was no Evidence of Attack by MoS_2 on Stainless Steel from 700°F to 1000°F"

d. N. E. Primisel and G. S. Mustin Corrosion 7, 377-89(1951)

Prevention of Corrosion in Naval Aircraft

"MoS_2 Offers Great Promise in Preventing Fretting Corrosion when Oscillatory Motion is the Main Concern"

e. H. C. Davis and J. Houseman Met/Phys 328, 1960

Corrosion Tests of MoS_2 in Aircraft SPAR Joints

"We Found that Aluminum Alloy/Steel Joints Containing MoS_2 Anti Sieze Compound (Spec D. T. D. 5530) are Unlikely to Corrode when Exposed to Rural Atmosphere Under Static Load Conditions"

f. Stainislaw Maciaszek Chemik (Gliwice) 18-20-3 (1965) Pol.

MoS_2 as a Lubricating Agent

"The Application of MoS_2 is Based on its Lubricating Properties for Metals without Causing any Corrosion (although certain sources say otherwise)"

g. F. Calhoun RIA U. S. Dept. Commerce AD 291,052 21 pp(1962)

Wear and Corrosion Tendencies of MoS_2 Containing Greases

"MoS_2 Promoted Rusting of Ferrous Metals when Added to Grease"

Our own experience shows that MoS_2/graphite coatings bonded with water glasses neither contribute to or offer much protection to corrosion susceptible metals in the presence of water vapor. However the MoS_2/graphite coatings bonded with organic resins or glass do offer a degree of corrosion protection.

It is not our policy to depend on dry lubricant films for corrosion protection in the presence of water vapor and oxygen; therefore, where corrosion may be a problem it is standard practice to recommend corrosion resistant substrates. Information received from Rocketdyne shows that all SSME components lubricated with bonded MoS_2 films are manufactured of either titanium or Inconel 718, neither of which are corrosion susceptible.

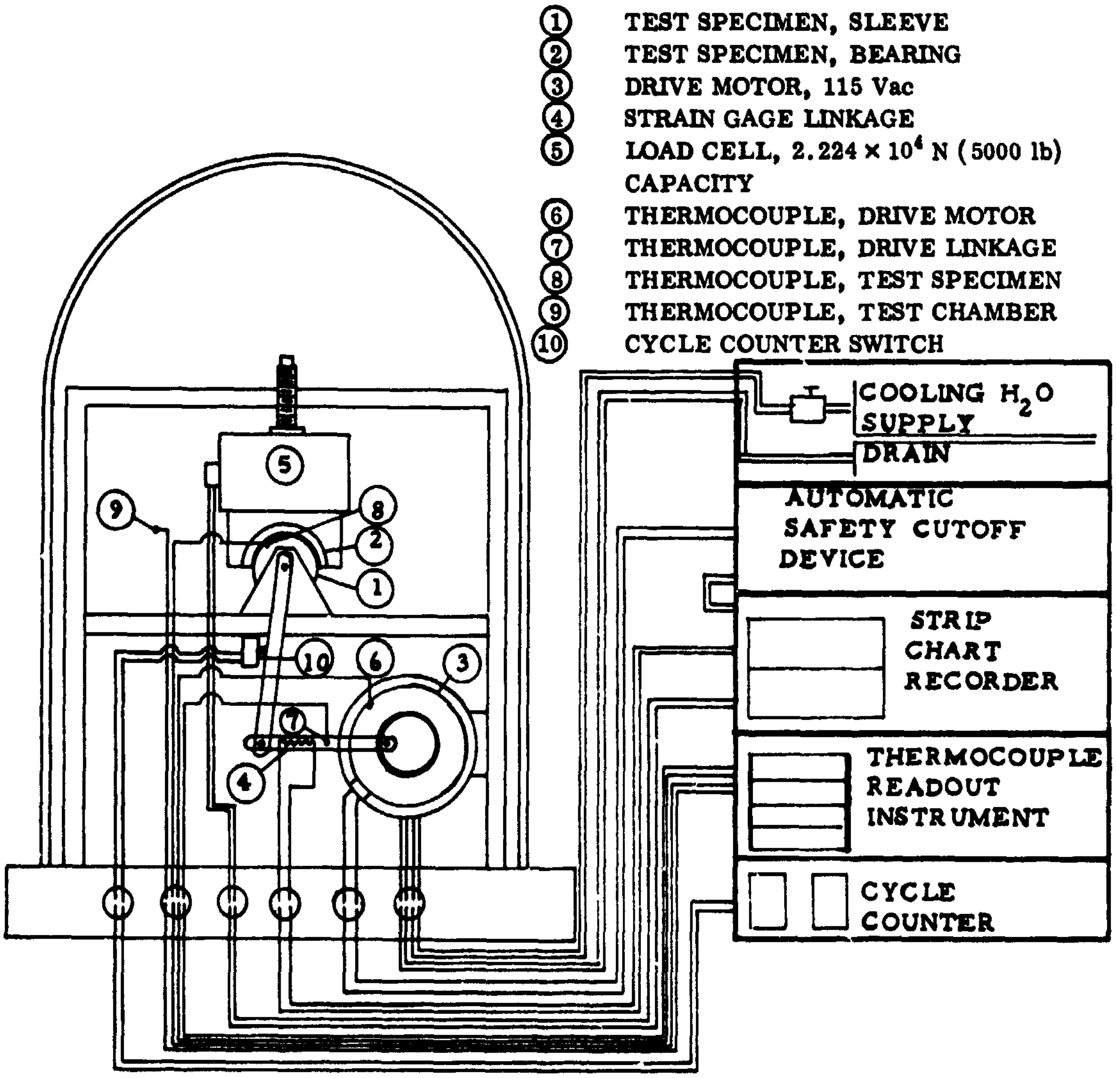


Figure 1. Gimbal test set-up schematic.

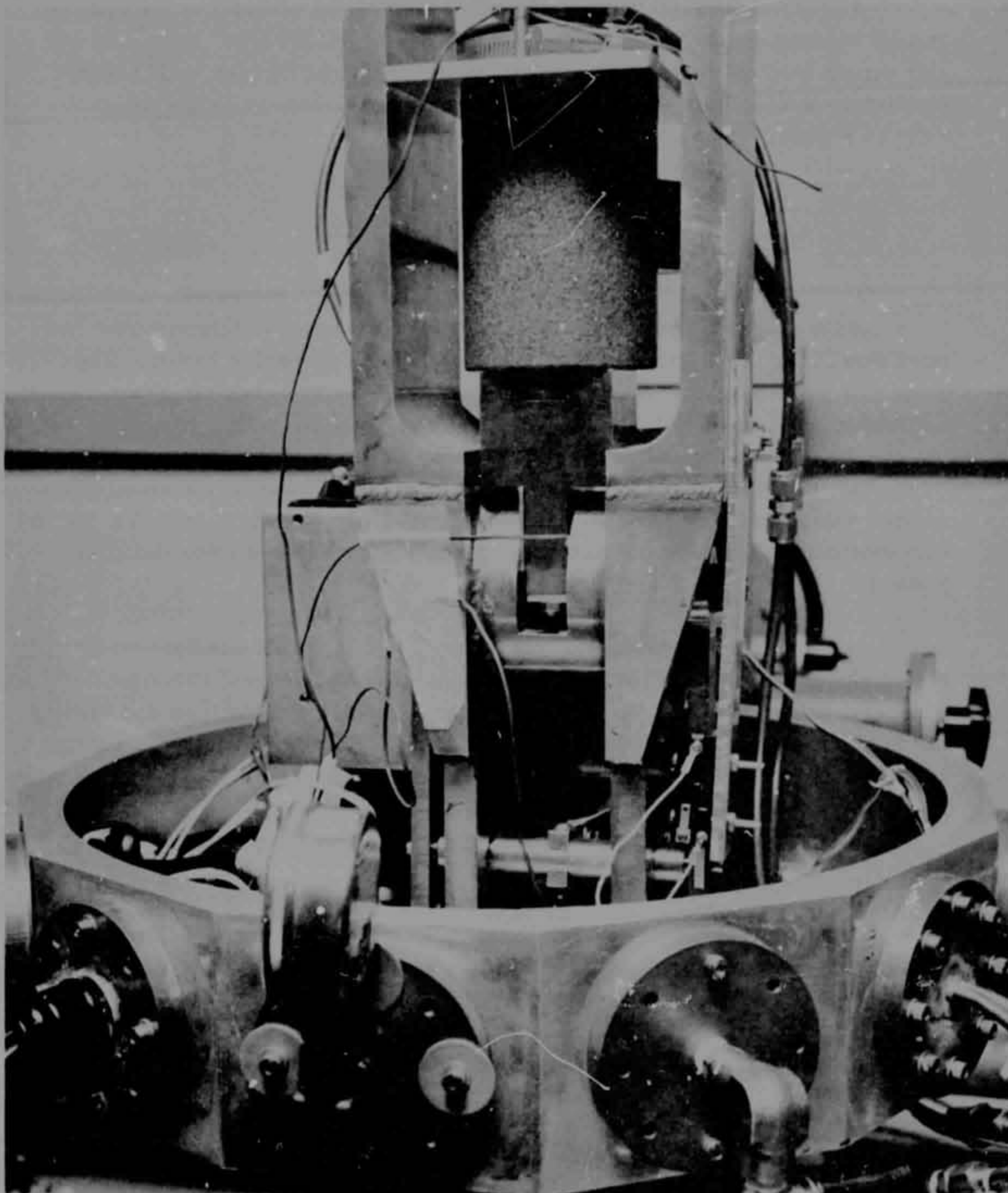


Figure 2. Gimbal test set-up.

II. TEST EQUIPMENT

A test mechanism was adapted for this program utilizing an oscillating journal bearing which could be loaded to the desired 1.379×10^8 N/m^2 (20 000 psi) stress load on the bearing surface as it was moved through an 11° angular oscillatory motion by an electric motor. This mechanism is shown schematically in Figure 1 and pictorially in Figure 2.

III. TEST PROCEDURE

A formal test procedure was prepared at the onset of this program and consisted of much the same information as has been presented herein. The basic test procedure was utilized for all test samples and consists of the following:

a. Each test specimen was identified with a permanently marked serial number which was coded in accordance with the basic substrate material and dry film lubricant. These serial numbers and code identifications are listed in Table 1.

b. The test specimen set consisting of one P/N ME-8163 sleeve or clevis and one P/N ME-8164 bearing was installed in the oscillation test apparatus in accordance with test schematic Figure 1, and the load was applied to the mechanism to produce the 1.379×10^8 N/m^2 (20 000 psi) stress loading required.

c. All instrumentation was double checked for proper operation prior to start of the oscillatory motion.

d. The first 500 cycles of operation on each specimen were used to stabilize the system and the static load was readjusted as necessary to maintain the 1.379×10^8 N/m^2 (20 000 psi) loading.

e. Installation of the bell jar and initiation of the vacuum pumpdown was accomplished after the system had operated 500 cycles and the loads had stabilized.

f. Variables were monitored throughout the tests and recorded at 10 500, 1000, and subsequently at 4000 cycle intervals. The static load and friction force (F_f) were monitored via load cell and strain gages and continuously recorded on a two channel strip chart recorder. The system was equipped with a safety cutoff which was triggered from the F_f readout strip chart so that any time the friction force exceeded approximately 88.964 N (20 lb) the drive motor was stopped.

g. The test specimens were left in the oscill ng mechanism until there was a sudden increase in the F_f indicating that the lubricant had broken down and metal to metal contact had been encountered.

h. The specimens were examined after the test to evaluate the failure condition. Typical examples of the test specimens are shown in Figure 3.

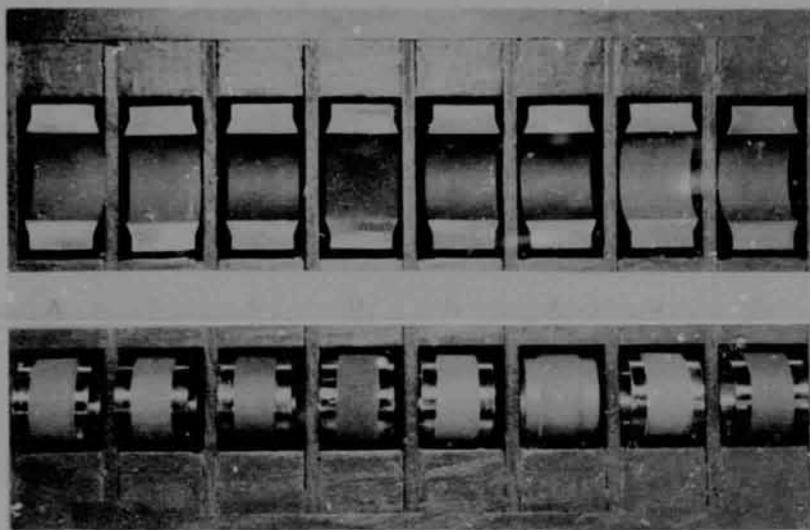
IV. ENGINEERING CALCULATIONS

A. Projected Area

The projected area is the area of the test specimen which supports the static load. This area is the cross section area of the bearing in a plane perpe dicular to the load. For this particular case, the projected area is simply the diameter of the bearing multiplied by the race width, or $1.59 \times 10^{-2} \times 7.62 \times 10^{-3}$ m $= 1.212 \times 10^{-4}$ m^2 (0.6266×0 300 in. = 0.188 in.^{2}).

B. Static Load

Since the design stress loading for the SSME gimbal bearing is 1.379×10^8 N/m^2 (20 000 psi), it was desirable to simulate this stress level even though the test specimens were scaled down in size. The stress load is simply the static load divided by the projected area which was previously calculated. From this we see that a static load of 1.672×10^4 N (3760 lb) is required to yield $1.672 \times 10^{-4} \div 1.212 \times 10^{-4} = 1.379 \times 10^8$ N/m^2.



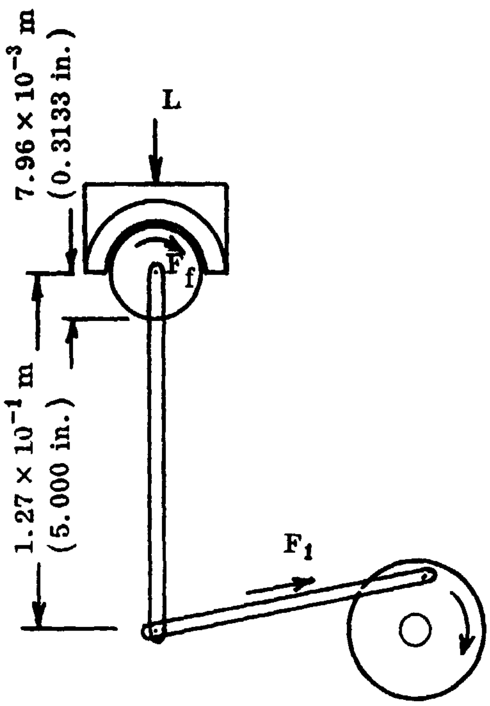
a. Prior to test.

b. After test.

Figure 3. Typical test specimens.

C. Friction Force

By definition, the F_f is the force acting on the specimen at the bearing surface tending to stop motion, e.g., F_f acts in the opposite direction to motion. The force required to overcome the F_f can be calculated as follows:



T_1 = Torque, m-N, produced by drive mechanism

L = Static load, N

F_f = Friction force, N

F_1 = Drive link force, N

C_f = Coefficient of friction at the bearing surfaces

T_f = Torque, m-N, produced by friction force

The drive link force was measured via a calibrated strain gage and this force was continuously monitored by use of a strip chart recorder. This force was used in calculating the F_f and then the coefficient of friction (C_f). Torque on the bearing specimen required to overcome friction is equal and opposite in direction to the torque caused by the F_f. Both of these torques are about the pivot point of the bearing specimen; however, the F_f acts at a moment arm length of only 7.96×10^{-3} m whereas the drive link force is acting at a moment arm length of 1.27×10^{-1} m. From this it is concluded that the relationship between the two forces is as follows:

$$T_f = T_1 = F_f \times 7.96 \times 10^{-3} = F_1 \times 1.27 \times 10^{-1}$$

$$F_f = \frac{1.27 \times 10^{-1} \times F_1}{7.96 \times 10^{-3}} = 15.959\ F_1$$

D. Coefficient of Friction

By definition, C_f is equal to F_f divided by the static load; thus, using the relationship previously established between the F_f and the drive link force,

$$C_f = \frac{15.959\ F_1}{L} \quad .$$

The C_f was calculated by this method and used for comparison of the various lubricant and substrate material combinations selected for evaluation for this test program.

V. TEST RESULTS

Much strip chart data and considerable other temperature, vacuum, and cyclic duration data were collected during this test program. To reduce these data to a form that could be used to compare each lubricant/ substrate combination with the others, seven different data points were selected as being most significant; six of these are C_f values and the other one is the total duration or life of the test specimen. These significant data points are discussed in the following paragraphs.

A. 0-10 Cycles

These data were considered important because the actual vehicle application will surely include this occurrence. If the F_f are too high during the first few movements or gimbals of the SSME, permanent damage could result to the bearing which might contribute to a catastrophic failure at a later date.

B. 500 Cycles

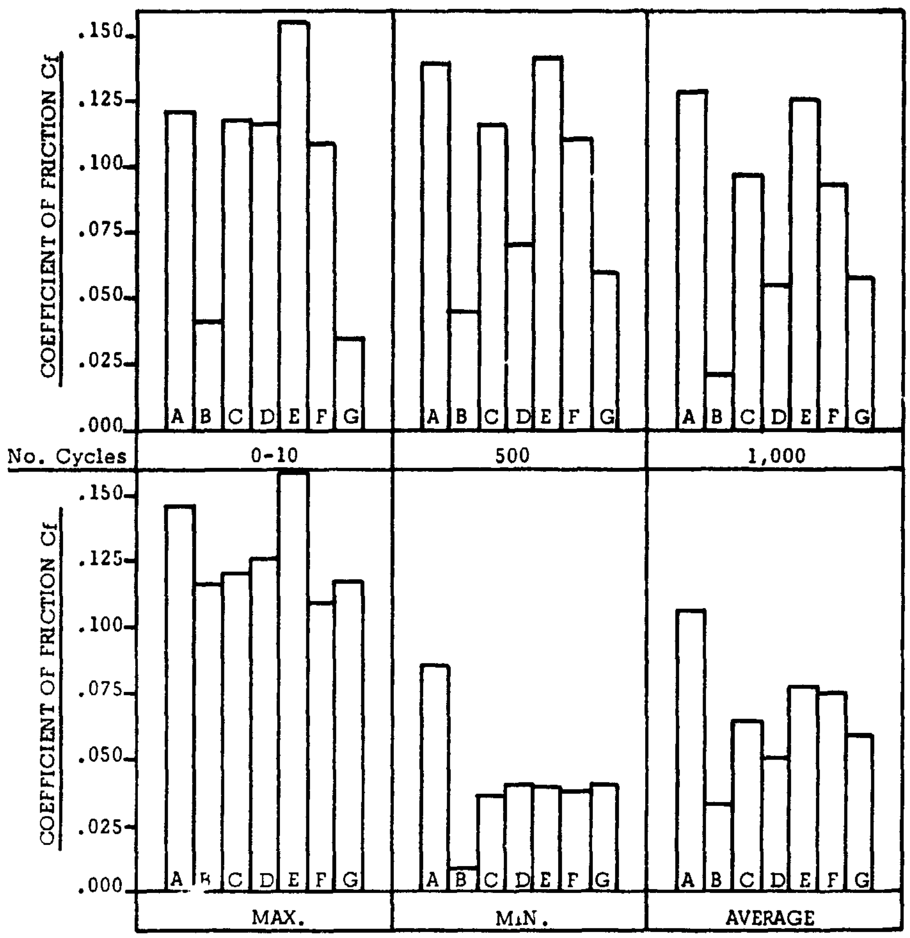
The test specimens were new when installed in the test setup and loaded. The excess lubricant had not been worn off or burnished in, and stabilized clearances had not been established. During this first 500 cycles of operation, the static load changed considerably and had to be readjusted. Since the static load was applied via a positive displacement (screw thread) method, it had to be done inside the bell jar or before the bell jar was installed. This is not different from what the actual SSME gimbal bearings will experience because considerable gimbaling will be done at standard atmospheric conditions during assembly and prelaunch checkouts. This data point is important and is comparatively graphed in Figures 4 through 7.

C. 1000 Cycles

This was considered an important data point because it gives an opportunity to compare the effect of vacuum on the different lubricant/substrate material combinations (vacuum was imposed at 500 cycles). These data are representative of the friction which can be expected during flight.

D. Max

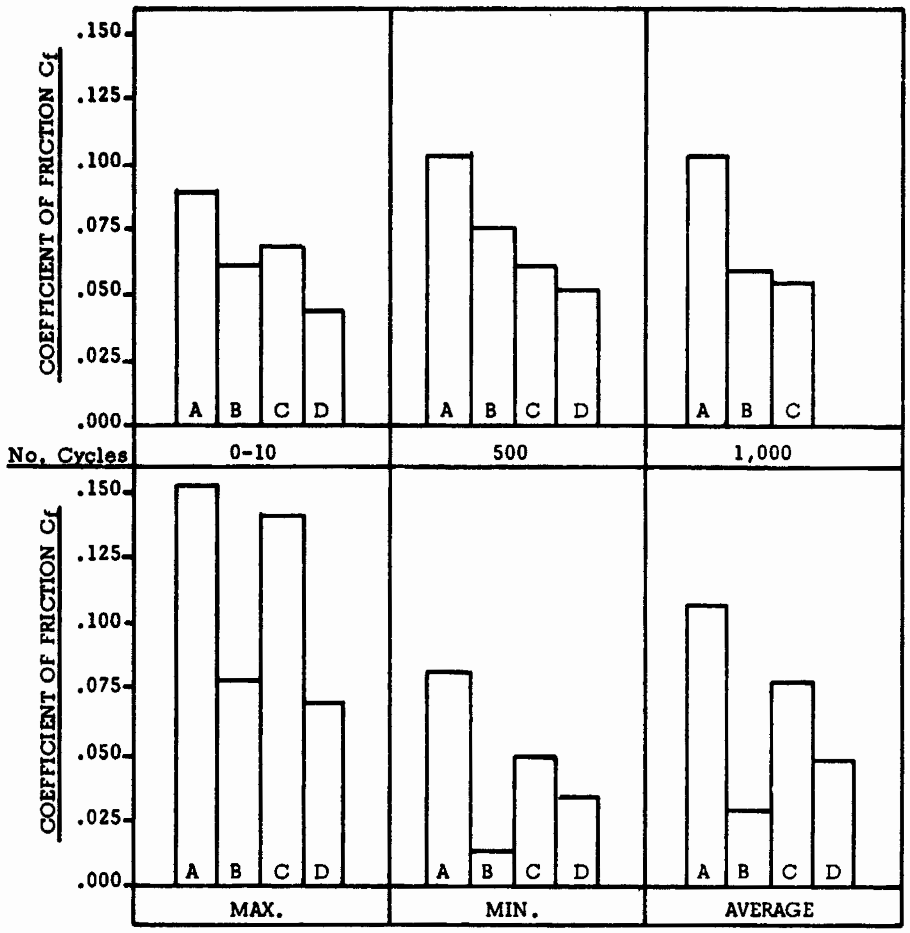
The maximum C_f encountered at any time during test of any specimen was considered important because this is a situation which could happen on the flight hardware. No lubricant/substrate material would be acceptable with a C_f over approximately 0.15 because this would put excessive load on the structure or could cause permanent damage to the gimbal bearing surfaces. It should be noted that all of the lubricants tested on titanium exhibited a coefficient of friction greater than 0.1 at some time during the test; however, on most of the specimens, this was a short duration high friction. This is not considered a serious problem on any of the lubricants except for lubricants (A) and (D).



Notes: 1. Upper bar graphs depict C_f at sta.· of test 0-10, after 500, and after 1000 cycles operation.

2. Substrate material for all specimens is Ti-6Al-6V-2Sn.
3. All tests werc made at 23.9 ± 5.5°C and 1.379×10^8 N/m^2.
4. The firs· 5υ0 cycles of the tests were at one atmosphere.
5. All tests after 500 cycles were at approximately 2×10^{-5} torr vacuum.
6. Data depicted are average of testing two specimens except (F) and (G) are based on one sample.
7. Max. and min. C_f values are not averages but are absolute values including all like specimens.
8. Average data depicted are C_f values for the duration of tests for all like specimens.
9. Code letters on the bar graphs correspond to lubricant code letters of Tables 2 and 3.

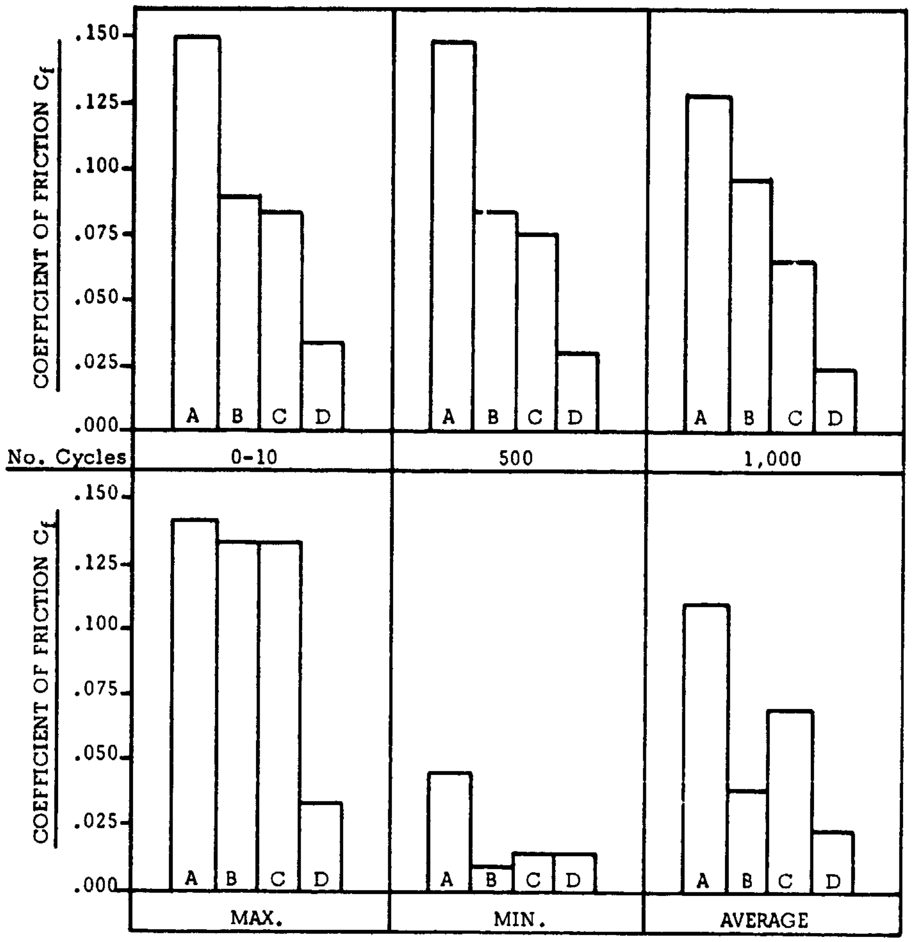
Figure 4. Bar graphs depicting C_f comparison of lubricants used on titanium.



Notes: 1. Upper bar graphs depict C_f at start of test 0-10, after 500, and after 1000 cycles operation.

2. Substrate material for all specimens is chrome plated titanium.
3. All tests were made at $23.9 \pm 5.5°C$ and 1.379×10^8 N/m^2.
4. The first 500 cycles of the tests were at one atmosphere.
5. All tests after 500 cycles were at approximately 2×10^{-5} torr vacuum.
6. Data depicted are average of testing two or three like specimens.
7. Max. and min. C_f values are not averages but are absolute values including all like specimens.
8. Average data depicted are C_f values for all like specimens for the duration of the tests.
9. Code letters on the bar graphs correspond to lubricant code letters of Tables 1 and 2.

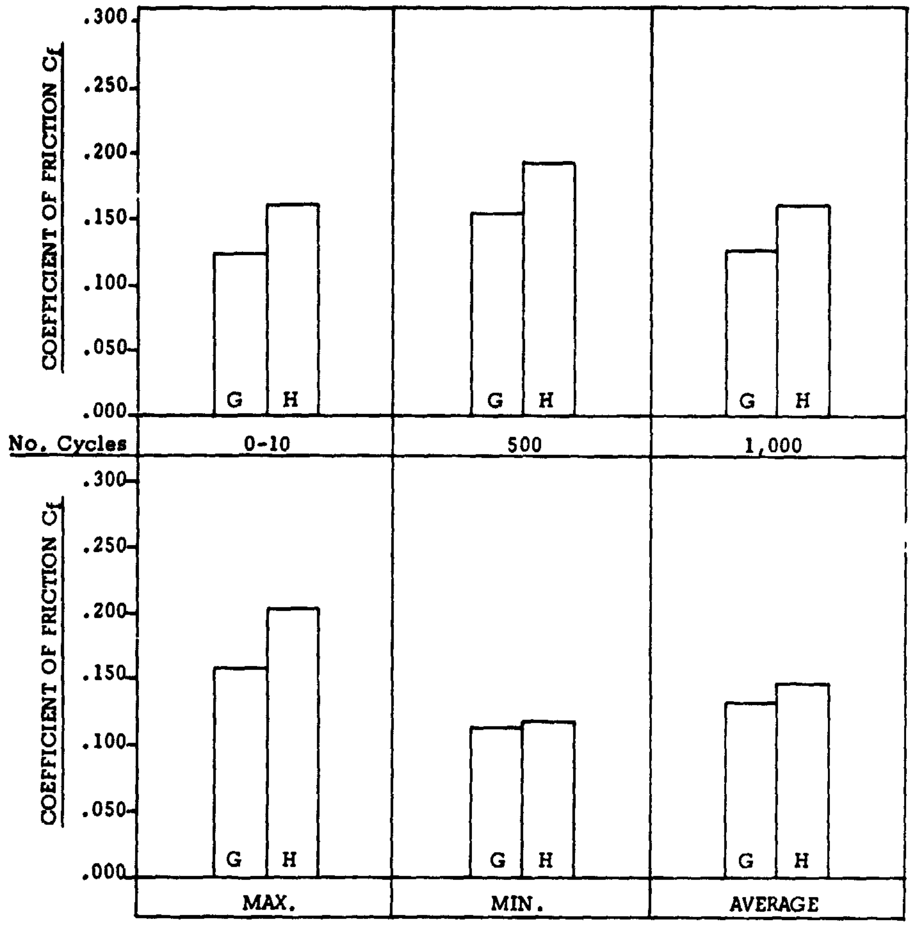
Figure 5. Bar graphs depicting C_f comparison of lubricants used on chrome plated titanium.



Notes: 1. Upper bar graphs depict C_f at start of test 0-10, after 500, and after 1000 cycles operation.

2. Substrate material for all pins is Ti-6Al-6V-2Sn.
3. Substrate material for all clevises is 440 C steel.
4. All tests were made at 23.9 ± 5.5°C and 1.379×10^8 N/m^2.
5. The first 500 cycles of tests were at one atmosphere.
6. All tests after 500 cycles were at approximately 2×10^{-5} torr vacuum.
7. Data depicted are average of testing two or three like specimens.
8. Max. and min. C_f values are not averages but are absolute values including all like specimens.
9. Average data depicted are C_f values for all like specimens for the duration of the tests.
10. Code letters on the bar graphs correspond to lubricant code letters of Tables 1 and 2.

Figure 6. Bar graphs depicting C_f comparison of lubricants used on titanium and 440 C steel.



Notes: 1. Upper bar graphs depict C_f at start of test 0-10, after 500, and after 1000 cycles operation.
2. Substrate material for all specimens is 440 C steel.
3. All tests were made at $23.9 \pm 5.5°C$ and 1.379×10^8 N/m^2.
4. The first 500 cycles of the test were at one atmosphere.
5. All tests after 500 cycles were at approximately 2×10^{-5} torr vacuum.
6. Data depicted are average of testing two or more like specimens.
7. Max. and min. C_f values are not averages but are absolute values including all like specimens.
8. Average data depicted are C_f values for all like specimens for the duration of the tests.
9. Code letters on the bar graphs correspond to lubricant code letters of Tables 1 and 2.

Figure 7. Bar graphs depicting C_f comparison of lubricants used on 440 C steel.

E. Min

The minimum friction exhibited by any one specimen at any time during the test program was plotted to give some indication of the relative lubricating ability of the various lubricants under ideal conditions. These data are shown in Figures 4 through 7. These data should not be used exclusively in establishing design loads because they are the very best lubricating characteristics exhibited at any time and are not nominal values.

F. Average

Another measure of the lubricating ability of the various lubricants was comparatively plotted in Figures 4 through 7 as the average C_f for all like specimens. These data were derived by multiplying the C_f by the number of cycles that the friction was constant, totalling all of these products, and then dividing by the total number of cycles the specimen lasted. These data are based on tests of all like specimens.

G. Duration

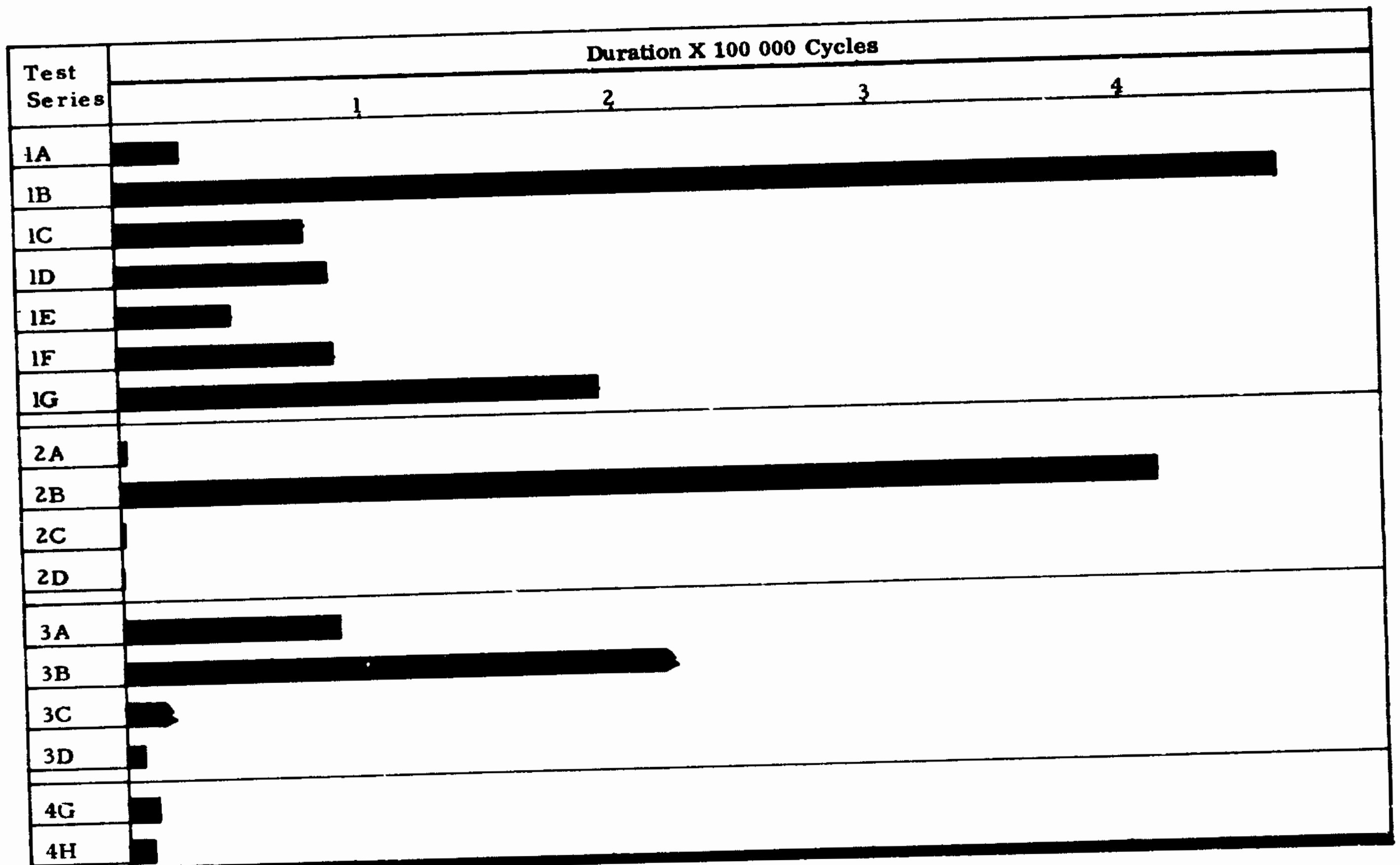
The duration or total number of cycles each lubricant/material combination withstood prior to galling or metal to metal contact is a very important comparison criterion. These data are shown in Table 3 and are also plotted for comparison in Figure 8. It is quite obvious that lubricant (B) is the superior lubricant from the standpoint of endurance, enduring over 450 000 cycles which is more than twice that of the next nearest candidate.

TABLE 3. ENDURANCE COMPARISON

Test Series	Duration (1000 cycles)		
	Max. Life	Min. Life	Avg. Life
1A	40	15	27.5
1B	746	175	460.5
1C	77	73	75
1D	91.5	77	84.25
1E	53	36.9	45
1F	85.5	85.5	85.5
1G	191.4	191.4	191.4
2A	2.3	<1	<1.65
2B	507	316.8	412
2C	1.2	1.2	1.2
2D	<0.8	<0.5	<0.65
3A	136.6	34.7	85.65
3B	401	>30[a]	>215.5[a]
3C	2	>30[a]	>16[a]
3D	10.4	5.5	7.37
4G	19	3.5	11.25
4H	14	6	10

a. These data are incomplete because the tests were terminated prior to failure.

Note: Test series numerals and letters correspond to substrate material and lubricant code letters, respectively (Tables 1 and 2).



Note: Test series numerals and letters correspond to substrate material and lubricant code letters, respectively. See Tables 1 and 2.

Figure 8. Endurance comparison bar graph.

VI. CONCLUSIONS

The original design of the SSME gimbal bearing utilized titanium material with a dry film lubricant (A). The titanium was selected because of its lighter weight and, even though other substrate materials were evaluated as a part of this program, none of the alternates provided significantly superior characteristics. The titanium base material was not found to be a contributing factor in the original failure during DVS testing; therefore, there is no obvious reason for changing from the titanium bearing substrate material.

Based on the aforementioned conclusions, the detailed comparison and evaluation was limited to the series 1 tests which were on specimens made of Ti-6Al-6V-2Sn. These data are graphically depicted in Figures 4 and 8 and in Table 3.

Lubricants (B) and (G) exhibited similar friction reducing capabilities throughout the test program; however, when compared from a standpoint of endurance, lubricant (B) was considerably superior. Lubricant (G) was, however, much superior to all the other lubricants tested with the exception of (B).

It is of interest to note that the C_f exhibited by the lubricant (A) was considerably higher than any of the other candidates. In fact, the overall program average of lubricant (A) was over 25 percent higher than the next highest candidate, lubricant (F).

It is also significant that lubricant (A) was the shortest lived of all lubricants tested, lasting only 27 500 cycles whereas the next lowest candidate was lubricant (E) which endured 45 000 cycles.

It was concluded from this test program that any one of the alternate candidate lubricants tested on titanium would be better for the particular application of the SSME gimbal bearing than the lubricant (A) which was selected during original design and failed during full scale DVS testing.

Preliminary data from these tests and from supplemental test at Rocketdyne have provided necessary justification for changing engineering drawings to specify lubricant (B) in lieu of lubricant (A). This change has been incorporated and it is believed that no further action is necessary. No further problem with respect to the SSME gimbal bearing lubrication is anticipated.

APPROVAL

AN EVALUATION OF DRY FILM LUBRICANTS AND SUBSTRATE MATERIALS FOR USE ON SSME GIMBAL BEARINGS

By J. A. Harp

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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